1996

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Repository Citation

Desmond, Eric D.; Ward, Andrew D.; Fausey, Norman R.; and Workman, Stephen R., "Comparison of Daily Water Table Depth Prediction by Four Simulation Models" (1996). *Biosystems and Agricultural Engineering Faculty Publications*. 211.
https://uknowledge.uky.edu/bae_facpub/211

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Notes/Citation Information

Published in *Transactions of the ASAE*, v. 39, issue 1, p. 111-118.

Digital Object Identifier (DOI)

https://doi.org/10.13031/2013.27487

COMPARISON OF DAILY WATER TABLE DEPTH PREDICTION BY FOUR SIMULATION MODELS

E. D. Desmond, A. D. Ward, N. R. Fausey, S. R. Workman

ABSTRACT. *The Agricultural Drainage And Pesticide Transport (ADAPT) model was compared to the water management simulation models DRAINMOD, SWATREN, and PREFLO. SWATREN and PREFLO are one-dimensional finite-difference models while ADAPT and DRAINMOD are one-dimensional mass balance models. ADAPT, an extension of the computer model GLEAMS, also provides chemical transport information. All four models were tested against field data from Aurora, North Carolina. Observed water table depth data were collected during 1973 through 1977 from a water table management field experiment with three subsurface drain spacing treatments of 7.5, 15, and 30 m.*

Both the standard error of estimate and the average absolute deviation were computed between measured and predicted midpoint water table depths. For the five-year period ADAPT, DRAINMOD, SWATREN, and PREFLO had standard errors of estimated water table depth of 0.18, 0.19, 0.19, and 0.18 m and absolute deviations of 0.14, 0.14, 0.14, and 0.14 m, respectively. The results show good agreement between the models for this experimental site and encourage the further adoption of ADAPT to predict chemical transport.

Keywords. *ADAPT, Hydrologic modeling, Water table management.*

Using water table management practices to help maintain agricultural productivity and profitability without causing any degradation of water quality, is important for many soils in the United States. In 1985, 44 million ha of agricultural land benefited from drainage improvements (USDA, 1987). The DRAINMOD model was developed to aid in the design and evaluation of shallow water management systems (Skaggs, 1978). Management systems modeled by DRAINMOD include subsurface and surface drainage, subirrigation, controlled drainage, and surface irrigation. An important feature of the model is the ability to provide information on the influence of excess and deficit water stresses on relative crop yields.

The need for water table management systems is not unique to U.S. agriculture. The Soil Water and Actual Transpiration Rate (SWATREN) drainage simulation model was developed to aid in the design of subsurface drainage systems in Europe (Feddes et al., 1978). The model employs a finite difference solution to the one-dimensional Richards equation. The model computes the water movement in a vertical section of the soil profile. Workman and Skaggs (1989) modified SWATREN to simulate a fluctuating water table that reaches the soil surface. SWATREN and DRAINMOD are the most widely used water table management models in Europe and the United States, respectively.

The PREFLO model was developed by Workman and Skaggs (1990) to study the unsaturated and saturated movement of water in a soil profile. An objective in developing PREFLO was to simulate macropore flow of water from the soil surface directly to the water table. As with SWATREN, PREFLO employs a finite-difference solution to the Richards equation. Input parameters required for PREFLO are similar to those required for DRAINMOD.

Concerns about agricultural impacts on the environment have increased greatly during the past decade and little is known about the impacts (positive or negative) of water table management systems. In a recent review article Skaggs et al. (1994) noted:

> *Although research results are not totally consistent, a great majority of studies indicate that, compared to natural conditions, drainage improvements in combination with a change in land use to agriculture increase peak runoff rates, sediment losses, and nutrient losses. Nevertheless, sediment and nutrient losses from artificially drained croplands are usually small compared to croplands on naturally well-drained uplands.*

Article was submitted for publication in August 1994; reviewed and approved for publication by the Soil and Water Div. of ASAE in September 1995.

Salaries and research support provided by state and federal funds appropriated to the Ohio Agricultural Research and Development Center, The Ohio State University. Manuscript No. 133-94. This research was conducted as part of the Ohio Management Systems Evaluation Area (OMSEA) project which is a cooperative research and educational effort of the USDA-Agricultural Research Service, the USDA-Cooperative States Research Service, the Ohio Agricultural Research Development Center, and the Ohio State University Extension at The Ohio State University, the U.S. Geological Survey, the USDA-Extension Service, the U.S. Environmental Protection Agency, and other state and federal agencies.

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The Agricultural Drainage And Pesticide Transport (ADAPT) [C. Alexander, "A model to simulate pesticide movement into drain tiles" (M.S. thesis, Dept. of Agricultural Engineering, The Ohio State University, Columbus, 1988)] computer model is a daily model which was developed to simulate the quantity and quality (pesticides, sediment, and nutrients) of water flows from water management systems. At the time ADAPT was first conceived there was no water management simulation model that adequately predicted chemical transport. The expectation was that information from ADAPT would be useful in determining best management practices (BMPs) that minimize the impact of agricultural production on the environment. Modeling approaches of the major processes employed by each model are listed in table 1.

The objectives of this study were to:

- Compare ADAPT estimates of daily midpoint water table elevations with observed data.
- Compare the performance of the ADAPT model in predicting daily water table elevations with results from DRAINMOD, SWATREN, and PREFLO.
- Evaluate the sensitivity of predicted hydrologic responses to changes in a selected number of ADAPT input parameters.

ADAPT MODEL DESCRIPTION

The ADAPT model was developed as an extension of the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987). GLEAMS hydrology algorithms were augmented with subsurface drainage, subsurface irrigation, and deep seepage algorithms. Other enhancements included adding the Doorenbos and Pruitt (1977) potential evapotranspiration (PET) estimator as an alternative to the Ritchie (1972) method; using a modified SCS curve number runoff model based on daily soil water content; including a Green and Ampt (1911) infiltration model based on suction at the wetting front; modeling snowmelt; and including empirical procedures to account for macropore flow. The above enhancements were described by Chung et al. (1992). A flow diagram illustrating the

Table 1. A comparison of modeling algorithms used by the ADAPT, DRAINMOD, SWATREN, and PREFLO water management simulation models

ITEM	ADAPT	DRAINMOD	SWATREN	PREFLO
Model approach	1-D mass balance midway between the drains	1-D mass balance midway between the drains	1-D finite difference solution Richards equation	1-D finite difference solution Richards equation
Detail of input data	Daily	Hourly	Daily	Hourly
Profile layers	5 layer profile and 9 computational layers	5 layer profile and 5 computational layers	5 layer profile with uniform node spacing	5 layer profile with non uniform node spacing
Weather data	Daily rain, average daily temperature, radiation, and data for ET calculation	Hourly rain, maximum and minimum temperature	Daily rain, data for ET calculation	Hourly rain, maximum and minimum temperature
Snowmelt	Ricca method as described by Chung (1992)	Not Modeled	Not Modeled	Not Modeled
Runoff	SCS curve number, adjusted as a function of daily soil water content	Remainder after computed mass balance in profile	Computed flux from Richards equation or SCS curve number method	Remainder after computed mass balance in profile
Macropore flow	Soil surface crack due to drying and evaporative demand or user defined	Not Modeled	Not Modeled	Structured percentage of pores open to the soil surface
Infiltration	Green-Ampt equation based on soil suction at the wetting front	Green-Ampt equation based on depth of water table	Richards equation	Richards equation
ET	Dorenbos-Pruitt, Ritchie, measured, or any external method	Thornthwaite (1948), measured, or any external method	Three methods, measured, or any external method	Thornthwaite (1948), measured, or any external method
Drainage/ Subirrigation	Kirkham's and Hooghoudt's equation.	Kirkham's and Hooghoudt's equation.	Ernst equation or six other choices	Kirkham's and Hooghoudt's equation.
Deep Seepage	Darcy's Law with unit gradient	Darcy's Law	Darcy's Law	Not Modeled
Chemical Transport	Pesticide, nutrient, and sediment in surface and sub-surface flows	Not Modeled in commonly available versions	Not Modeled in commonly available versions	Not Modeled

processes and the modeling technique employed in ADAPT is presented in figure 1. A daily water mass balance is performed by ADAPT at a position midway between subsurface drains. A summary of hydrologic changes to the model since the earlier report by Chung et al., (1992) are described in this article.

POTENTIAL EVAPOTRANSPIRATION

Potential evapotranspiration can be applied directly to the model in the case that daily data are available. These data can be measured pan evaporation data or calculated by an external PET method. The user may specify that PET be estimated by the Doorenbos and Pruitt or the Ritchie method which both require daily weather data. Actual evapotranspiration is a function of PET and leaf area. Soil water to supply evapotranspiration (ET) is taken from the top one-sixth of the root zone during early plant growth. As leaf area increases more of the root zone becomes available for ET extraction. When leaf area is at a maximum for the crop year ET is extracted from the entire root zone.

MACROPORE FLOW

Macropore flow was modeled after Pathak et al. (1989). The potential water volume available for macropore flow is the sum of evaporative demand since the previous rainfall event. A crack growth delay parameter (DACK), measured in days, pro-rates the volume available for macropore flow from 0% just after a rainfall event to 100% when a specified delay time is reached. A macropore flow event resets the sum of evaporative demand to zero. Additionally, the user can specify a fixed percentage of rainfall which is partitioned to macropore flow. The model does not actually model macropore flow processes, but simply diverts macropore flow from runoff directly to the water table within the daily time step of the model.

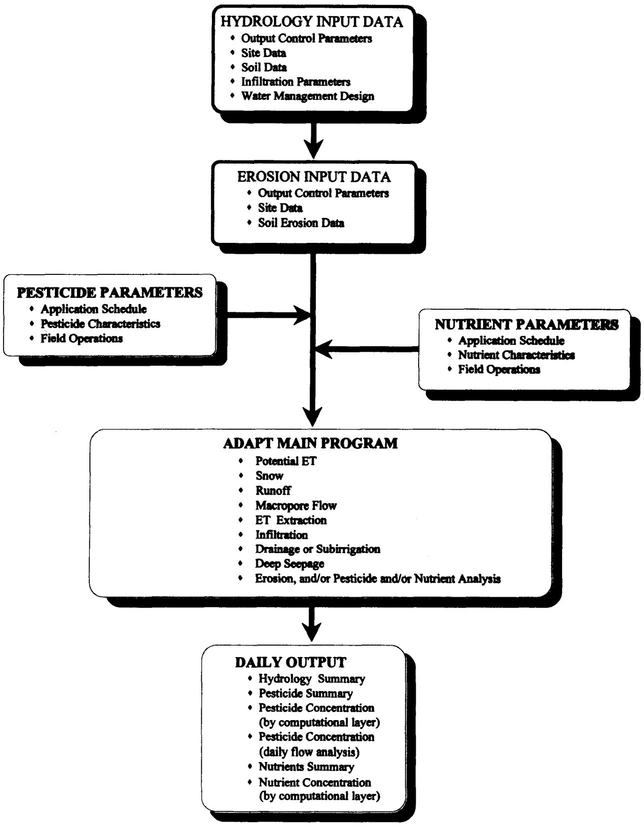


Figure 1–A flow diagram showing the major water balance processes in the water management simulation model ADAPT.

UNSATURATED SOIL WATER ESTIMATION

Previously the ADAPT model assumed that, after wetting, the soil water profile above the wetting front was at field capacity (Chung et al., 1992). However, the water content of a soil parcel in the unsaturated zone is a function of soil water tension forces and is a function of upward flux from the water table. The unsaturated soil water profile was thus changed to approximate the drained to equilibrium condition as shown in figure 2. This profile includes the "capillary fringe", a zone above the water table with a soil water content that is between field capacity and saturation. For a deep water table depth the model predicts a lower net soil water content than the field capacity condition while for shallow water table conditions the model predicts a higher net soil water content.

To apply this theory, ADAPT requires soil water retention data for each soil layer. As the water table drops due to drainage, deep seepage, and ET extraction, the water content above the water table also changes to match a higher tension condition. Upon reaching the water table, infiltrated water fills part of the profile to saturation and raises the water table.

Soil water retention data preferably are obtained from laboratory analysis of soil cores extracted from the field site or from field measurements. Alternatively, the user can employ data derived from approximate procedures (Van Genuchten and Nielson, 1985). The Soil Conservation Services Soils-5 database and their DMSOILS Program (Baumer, 1987) is commonly used for this purpose.

UPWARD FLUX

The water table may drop below the root zone depth as a result of subsurface drainage or deep seepage, but plant roots still have the ability to extract water from the water table through the soil matrix. This ability, called upward flux due to ET, is a function of the soil unsaturated conductivity and can be predicted from the theory of Maulem as discussed by Van Genuchten and Nielson (1985).

Upward flux is driven by a tension source, evaporation at the soil surface or plant roots. Plant roots are not located

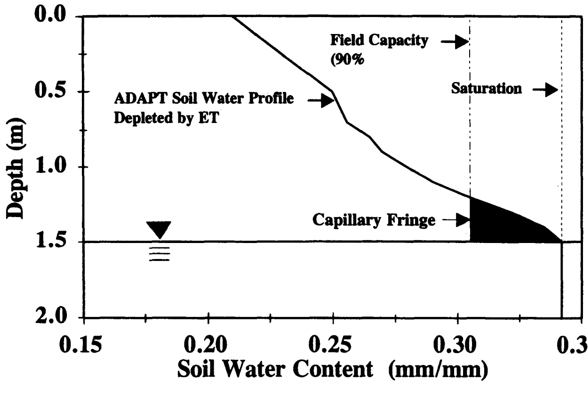


Figure 2–Soil water profile at equilibrium above a water table depth of 1.5 m as employed by the ADAPT program.

at a finite depth, but found in a zone of transient thickness. In ADAPT this transient thickness is currently modeled by specifying a fixed datum. The upper limit of this datum used in previous studies (Ward et al., 1993) is the soil surface. The lower limit is the maximum rooting depth. A lower datum increases the amount of water available to the plant roots directly supplied from the water table.

The best modeling strategy might be to relate the datum to transient changes in the root depth. A study is underway to join ADAPT with the crop growth model CROPGRO (Hoogenboom et al., 1993) and upward flux modifications will be made based on the best approach to satisfy plant development requirements in CROPGRO. In the interim, a fixed datum based on the midpoint between the soil surface and the maximum rooting depth has been used. This approach is compared with the use of the soil surface as the datum in figure 3. Both curves are parallel and separated by half the maximum root zone depth (0.3 m). To illustrate the importance of upward flux processes, suppose the water table depth dropped to 0.8 m. A datum fixed at the surface can supply 0.025 mm/h from the water table to satisfy ET demand (fig. 3) while a datum of 0.3 m can supply 0.2 mm/h, an eightfold potential increase. The upward flux relationship used here was generated by Skaggs (1978).

EXPERIMENTAL APPROACH

EXPERIMENTAL SITE

A goal of the field experiment was to measure the effectiveness of subirrigation in response to different subsurface drain spacings. The field site was located on the H. Carroll Austin farm near Aurora, North Carolina, and is described in detail by Skaggs (1978). The field has three drainage treatments with drain spacings of 7.5, 15, and 30 m placed side by side. Tomatly sandy loam (Typic Ochraquult) soil dominates the site with lesser amounts of Myatt sandy loam (Typic Ochraquult) soil and Torhunta sandy loam (Typic Humaquept) soil found mainly in the 7.5 and 15 m drain spacing treatments. All runoff and subsurface drainage flow discharged into a common ditch. Runoff water also flowed into the drainage ditch. During subirrigation the ditch water level was raised above the drain outlet level to a prescribed management level.

Water table level observation wells were placed midway between drains in each drainage treatment and a water level recorder was also placed on the outlet ditch. Daily water level data were recorded by these instruments. A tipping bucket rain gauge was placed on the site to record the hourly rainfall required for DRAINMOD. Pan evaporation data, measured at the field site, was used to derive daily PET values (Skaggs, 1978) for both DRAINMOD and ADAPT. Daily maximum and minimum temperature data were also collected at the site. These data were directly employed by all models in some form. For example, DRAINMOD and ADAPT used hourly and daily rainfall, respectively.

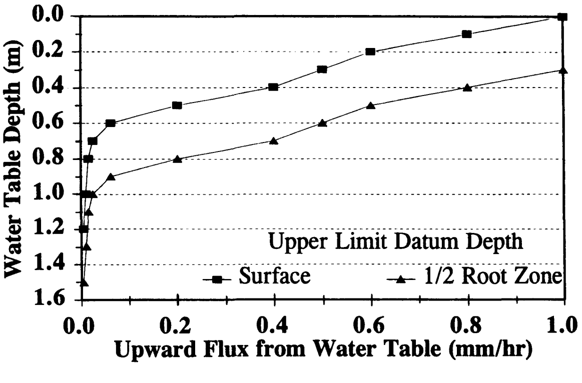


Figure 3–Upward flux available to satisfy plant ET directly from the water table for an upper limit datum at the soil surface and half the root zone depth.

MODEL EVALUATION

Daily observed field data from Aurora, North Carolina, were collected over a five-year period (1973 to 1977). The experimental site comprised three subsurface drain spacing treatments of 7.5, 15, and 30 m. Simulated daily water table depths from DRAINMOD and SWATREN were compared with these observed daily water table data by Workman and Skaggs (1989), while DRAINMOD and PREFLO were compared to the same observed data set by Workman and Skaggs (1991). Soil and drainage system input data common to those employed by Workman and Skaggs were applied to ADAPT. The standard error of estimates and absolute deviations between observed and predicted daily water table depth population means were calculated for the ADAPT model simulations. Drainage treatment means were examined on a yearly basis in addition to annual composite and five-year experimental summaries. Similar data were available for the other three models from the studies cited above.

The standard error is defined as follows:

$$s = \sqrt{\frac{\Sigma\left(Y_m - Y_p\right)^2}{n}} \qquad (1)$$

where

s = standard error (m)

Y_m = measured water table depth at the end of each day (m)

Y_p = predicted water table depth at the end of each day (m)

n = number of days for which data was collected

The average absolute deviation (α), also in meters, is defined as follows:

$$\alpha = \frac{\Sigma\left|Y_m - Y_p\right|}{n} \qquad (2)$$

MODEL INPUTS

Drainage system parameters used in all models are listed in table 2. All four models used some common site specific soil property and weather data (Skaggs, 1978). Several input data applied to ADAPT differ from those applied to DRAINMOD, SWATREN, and PREFLO due to differences in model requirements. For example, a growing season root depth function is required for DRAINMOD while ADAPT needs a maximum crop rooting depth based on cropping history, specific crop rooting depth, and leaf area index function. Workman and Skaggs (1989) describe input data used in the comparison of DRAINMOD and

Table 2. Drainage system parameters for the field site (Workman and Skaggs, 1989)

Drainage Design Parameter	Units	Treatment 1	Treatment 2	Treatment 3
Drain spacing	m	7.5	15.0	30.0
Drain depth	m	0.8	0.9	1.0
Depth to restrictive layer	m	1.26	1.50	1.74
Drain diameter	mm	102	102	102
Effective drain radius	mm	2.5	2.5	2.5

SWATREN while Workman and Skaggs (1991) describe input data for the comparison of DRAINMOD and PREFLO. We will therefore only present a description of drainage design and soil characteristics data applied to ADAPT. Simulations were run for each drain spacing treatment using field conditions, such as drain depth, associated with each treatment. Macropore flow was not simulated for this site.

Soil water characteristic data were measured using cores obtained from the top soil layer. Ideally soil water characteristic data for each layer should be used with ADAPT, but these data were not available. General soil properties used in ADAPT are presented in table 3. Further soils and site information were described by Skaggs (1978).

Leaf area index (LAI) curves used in DRAINMOD and SWATREN were acquired from Wilkerson (1987) for corn, soybeans and wheat, and Galston et al. (1980) for potatoes. These LAI data were synthetically generated. Corresponding leaf area data for ADAPT were taken from the GLEAMS database (Knisel et al., 1993) because these data were developed specifically for use in GLEAMS and ADAPT is an extension of this model. Leaf area data for GLEAMS are in a normalized form and presented in table 4. These data were interpolated between recorded planting and harvesting dates (table 5) to provide leaf areas at any date.

RESULTS AND DISCUSSION

MODEL COMPARISON

Yearly standard error of estimated water table depth means are presented in figure 4 for all models and drainage treatments. Absolute deviation between observed and estimated daily water table depth followed a similar trend to that of the standard error. A comparison was also performed between ADAPT simulations with the upward flux upper limit datum at the surface and the upper limit datum at 0.3 m, which is one half the root zone depth. For most years and treatments the ADAPT model gave the poorest results when the upward flux datum was the soil surface. However, if the upward flux datum was set to half the maximum root zone depth, the ADAPT model gave similar results to the other models. Ranges of ADAPT yearly mean standard errors for this case were 0.08 to 0.25 m, compared to 0.10 to 0.23 m for DRAINMOD, 0.09 to 0.29 m for SWATREN, and 0.07 to 0.24 for PREFLO. The overall mean standard error for ADAPT and PREFLO results was 0.18 and 0.19 m for DRAINMOD and SWATREN. No single model dominated the standard error statistics.

Table 3. General soil properties for Tomatly soil found at the Aurora, North Carolina, site as used in the ADAPT model (Skaggs, 1978)

Soil Property	Units	Layer 1	Layer 2
Thickness (average)	m	1	0.5
Porosity	mm/mm	0.342	0.342
Horizontal hydraulic conductivity	mm/h	10	30
Vertical hydraulic conductivity	mm/h	20	60
Wilting point water content	mm/mm	0.12	0.12
SCS curve number	Cond. II	80	NA
Effective rooting depth	m	0.6	NA
Soil evaporation parameter	mm/d$^{0.5}$	3.5	NA

Table 4. Growing season normalized leaf area, m^2/m^2 (Knisel et al., 1993)

Relative Growth Stage	Potato	Soybean	Corn	Wheat
0.0	0.00	0.00	0.00	0.00
0.1	0.10	0.15	0.09	0.47
0.2	0.25	0.40	0.19	0.90
0.3	0.43	1.90	0.23	0.90
0.4	0.63	2.60	0.49	0.90
0.5	2.23	3.00	1.16	0.90
0.6	2.62	2.96	2.97	1.62
0.7	3.00	2.92	3.00	3.00
0.8	2.65	2.30	2.72	3.00
0.9	2.48	1.15	1.83	3.00
1.0	2.15	0.50	0.00	0.00

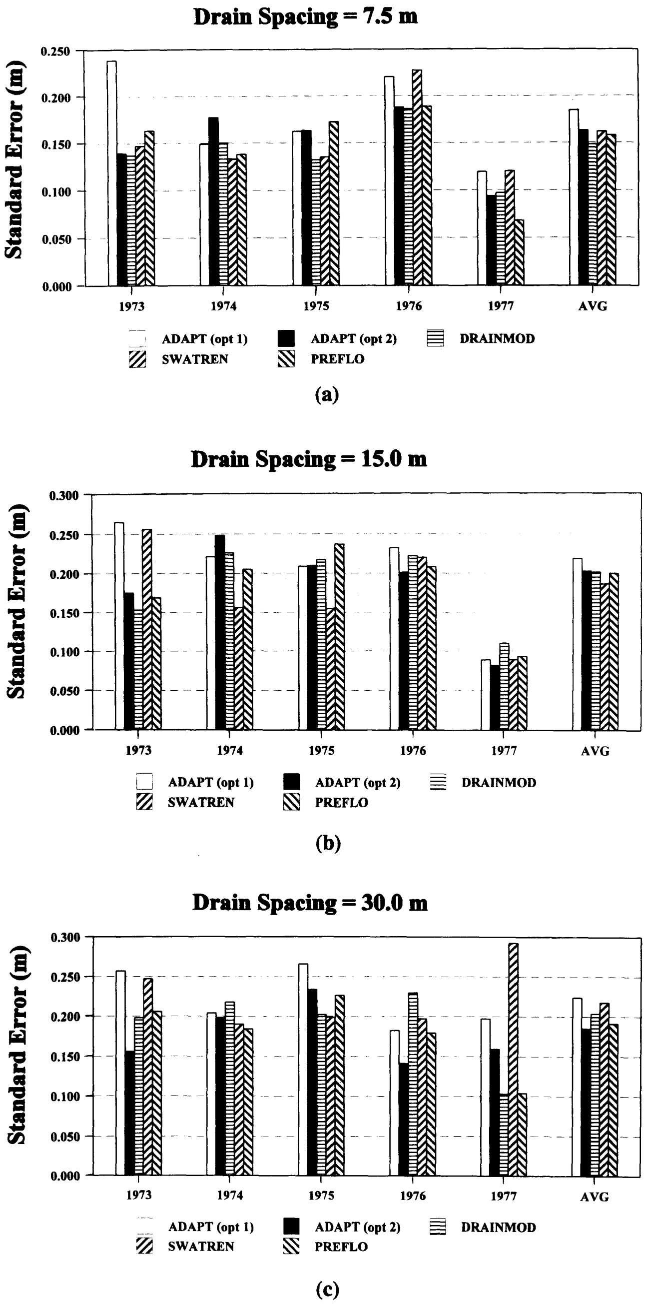
The absolute deviation results also indicate that there is little difference in the ability of any of the models to predict water table depths for this location. The mean absolute deviation rounded to 0.14 m for all models. All models exhibit both of the best and worst results.

The 1975 growing season water table depths simulated by ADAPT, for both cases of upward flux upper limit datum, are compared to observed data in figure 5 on the 7.5 m drain spacing treatment. The simulation using the ground surface datum underpredicted the water table depth, particularly when it fell near or below the subsurface drain depth as a result of high ET demand. Figure 5 also shows the model overpredicted the decline in the water table from days 150 to 180 and underpredicted the rise in the water table between days 240 to 290 when the upward flux upper datum was set at 0.3 m. Figure 6 demonstrates the effectiveness of the ADAPT model during nongrowing season months for the 15 m drainage treatment. In most cases both DRAINMOD and PREFLO tended to overpredict the water table depth (Workman and Skaggs, 1991).

Table 5. Cropping rotation for the field site from 1973 to 1977 (Workman and Skaggs, 1989)

Year	Crop	Plant Date	Harvest Date
1973	potato	3/10*	6/20
	soybean	7/17	11/14
1974	potato	3/10*	6/17
	soybean	7/10	11/27
1975	corn	4/21	9/10
	winter wheat	11/21	–
1976	winter wheat	-	6/16
	soybean	6/17	11/17
1977	corn	4/25	9/1*

* Approximate date for planting or harvest.



(a)

(b)

(c)

Figure 4–Standard error of estimated water table depth means for four water management simulation models under (a) 7.5-m, (b) 15-m, and (c) 30-m subsurface drain spacing. The ADAPT model was executed with the upward flux upper limit datum point at the soil surface (opt 1) and at one half the root zone depth (opt 2).

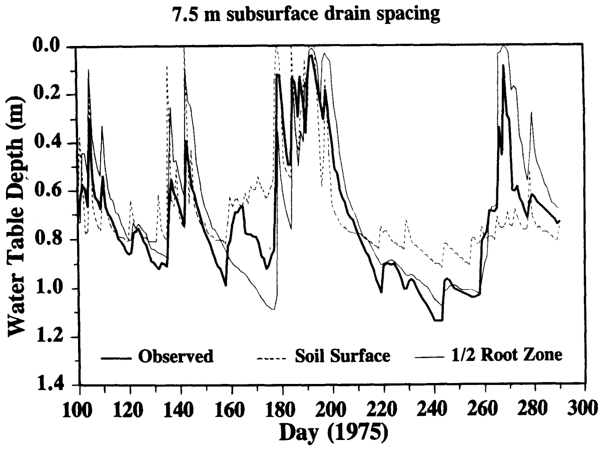


Figure 5–Observed daily water table depth profile compared to predicted data using ADAPT where the upward flux upper limit datum is modeled at the soil surface and at one half the root zone depth (0.3 m).

The sensitivity of the water table depth statistics to changes in the selected input parameters was also evaluated. Changes of up to ±50% in the root zone depth and leaf area resulted in changes of ±3% in the standard error and absolute difference between observed and predicted water table depths. Curve numbers in the range of 70 to 85 resulted in changes in the standard error and absolute difference of ±2%. A greater magnitude of change was associated with the saturated hydraulic conductivity and the upward flux (figs. 7 and 8, respectively). An improvement of about 10% in the standard error and 5% in the absolute difference might occur if the hydraulic conductivity was 25% less and the upward flux was 50% greater. The results show that runoff and drainage processes are more sensitive than the water table depth to changes in these input parameters. This is because the two are self-compensating and tend to offset each other.

GENERAL DISCUSSION

It is rare to find such a complete data set of water table elevations at a well-defined field site; this is invaluable for validating simulation models. The Aurora site lacks subsurface drainage and runoff flow information, but is a fairly easy system to model because of the relatively high hydraulic conductivity and soil uniformity. Three other field sites in Ohio are presently being used to further validate the ADAPT model (Ward et al., 1993). These sites have vastly different soil and climatic conditions that test the limits of the model as well as other components not addressed at the Aurora site. These components include snow melt, soil crusting, macropore flow in high clay soil, and water quality associated with runoff and subsurface flows.

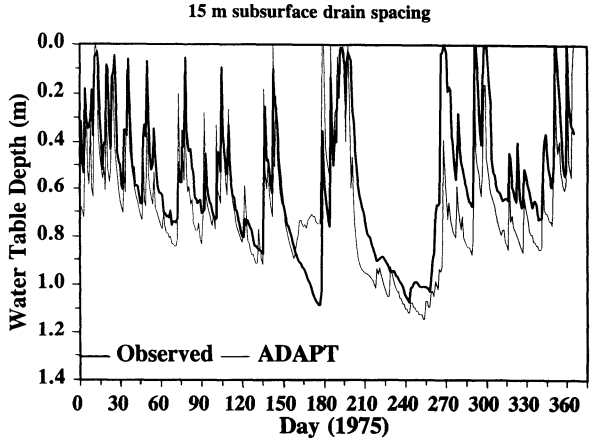


Figure 6–Observed daily water table depth profile compared to ADAPT-predicted data for the 15-m subsurface drain spacing treatment during 1975.

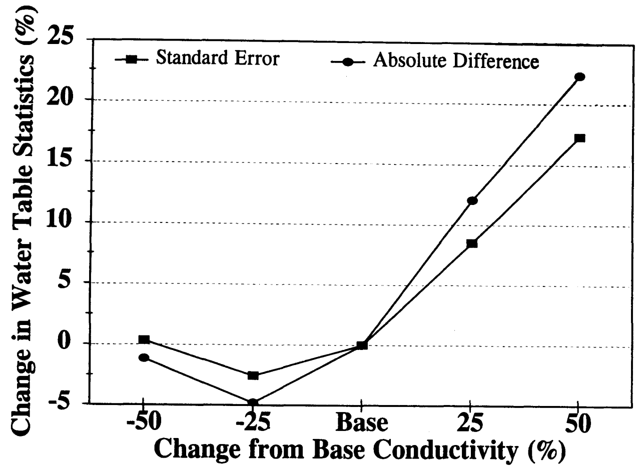


Figure 7–Sensitivity of predicted water table depth statistics to changes in soil hydraulic conductivity.

The GLEAMS model, from which ADAPT was created, was found to be insensitive to saturated hydraulic conductivity (K_{sat}, Knisel et al., 1991). This is in contrast to the sensitivity found for the ADAPT model. This is because GLEAMS models only the root zone and does not use K_{sat} to model percolation except when a very low K_{sat} value exists below the lowest horizon. In this case percolation may be limited for large rainfall or irrigation events. Infiltration, drainage, and subirrigation routines in the ADAPT model are very dependent on K_{sat} and thus ADAPT is sensitive to this value.

Chemical fate predictions performed by ADAPT depend on the accuracy of the hydrologic simulation. Data presented have indicated that ADAPT does simulate water table hydrology well, specifically at the Aurora site. The study by Chung et al. (1992) showed that ADAPT can simulate runoff and drainage processes. More recent studies demonstrated the ability of ADAPT to simulate pesticide discharges in runoff and drainage (Ward et al., 1993; Desmond et al., 1995). Additional studies at other sites will help evaluate the variety of conditions under which ADAPT can be employed.

With few exceptions, unmodified input and output data were employed by the authors. However, none of the models were intentionally calibrated though they would benefit from the procedure.

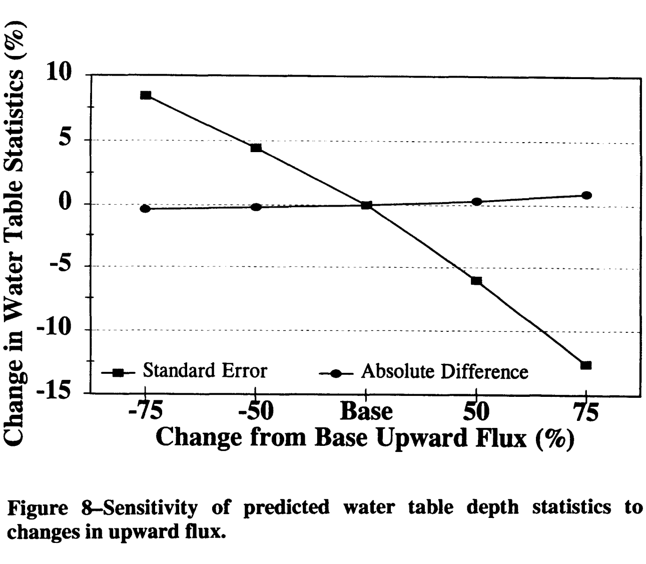


Figure 8–Sensitivity of predicted water table depth statistics to changes in upward flux.

CONCLUSION

Direct comparison of ADAPT with the three models, DRAINMOD, SWATREN, and PREFLO, showed that all models were capable of predicting water table depths with similar accuracy for the conditions tested. Standard errors and absolute deviations produced by ADAPT were very similar to those produced by DRAINMOD, SWATREN, and PREFLO when the upper upward flux datum was set to one half the maximum root zone depth in ADAPT.

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